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Future Opportunities for Photonics R&D

Photonics is a term used to describe the generation, manipulation, and detection of photons in a manner that is analogous to that of electrons in electronics. Most of us are familiar with one of today's better-known photonics devices: the laser. While extremely valuable for fiberoptic communications, lasers also have a variety of other very important applications such as optical memory, barcode readers, materials processing, and radar.

In the last 20 years, photonics has had an enormous impact on the communications industry. So successful has photonics been in providing greater capacity at lower cost that optical fiber has been installed at a rate that, at times, has exhausted production capabilities.

Photonics has also had a profound impact on the design and performance of military systems. The ability of photonics-enhanced weapons to strike with high precision, in many cases, has changed the nature of warfare. For example, the increased effectiveness of precision-guided munitions (PGM) has rendered "area bombing" nearly obsolete.

Another revolution in military strategy and tactics has occurred through the use of night vision equipment. A substantial operational advantage can be achieved if one set of armed forces can operate throughout the night, and the opposing forces cannot.

While technological advances in sensors, displays, and digital electronics have all made significant contributions, another photonic technology—optical interconnects—is set to further revolutionize the capabilities of military systems.

Although most familiar as a replacement for long-haul coaxial cable data transmission, optical interconnects have made impressive strides in shorter distance applications. Also, the ability of optical interconnects to process data during transmission offers an increase in functionality that normally is not found in electrical interconnects.

Many soon-to-be-developed photonics devices similarly will find an extensive range of new uses and, in each case, there will be a substantial improvement in performance and cost. The key to these new applications lies in the ongoing development of new materials, innovative device designs, and the integration at the chip level of diverse technologies such as photonics, electronics, and micro-electro- mechanical systems (MEMS).

The future opportunities that photonics will enable will use unique features of light to achieve a high level of performance that is not achievable through any other means. For example, two data-bearing beams of light can cross paths in free space without "shorting out" or causing mutual interference. This would be impossible with the use of wires.

Taking advantage of the unique properties of photonic devices is a dynamic area of research that is developing some surprising and truly revolutionary means to accomplish important, but otherwise difficult or impossible tasks.

Five of these areas that I will discuss include:

- Biophotonics
- Optics in computing
- Imaging
- Optical wireless
- Service-on-demand networks

In biophotonics, spectroscopy is a very useful tool for determining the chemical makeup of a substance. In a typical spectroscopic setup, white light passes through a sample and shines upon a grating that acts like a prism as it breaks the light into different colors, sending each color in a different direction. Some of the colors (or wavelengths) of the source are transmitted (completely or partially) by the sample, while others are absorbed (completely or partially). The detector records the transmission spectrum and the resulting spectroscopic "picture" provides a key to determining the chemical constituents present in the sample. Typical spectrometers can occupy several square feet of laboratory bench space and require highly trained personnel to maintain and operate the equipment. New technologies are emerging that offer the opportunity to shrink dramatically the size of this type of experimental apparatus and to make these analytical capabilities more accessible for use outside of a laboratory.

The approach taken is commonly called "spectrometer-on-a- chip" (SOC), which takes advantage of the powerful miniaturization tools and batch fabrication processes found in today's microelectronics industry. Large wafers can be produced containing thousands of tiny spectrometers, complete with all the required control and data-gathering electronics.

Microfluidics is an area of research that is developing very small components that transport very small quantities of liquid or gas on a chip. In addition to transport channels, researchers are developing ultrasmall pumps, valves, switches, pressure and flow-rate sensors, reactant holding tanks and reaction chambers for SOC-based spectroscopic applications. SOC, as well as other microfabrication technologies, could be used eventually to construct a complete laboratory on a chip. This technology will have a tremendous impact on future developments in medical equipment, environmental testing, and industrial process monitoring.

Computer architecture design represents an interesting insertion opportunity for photonics. The speed at which computers can process data has increased steadily and dramatically since the introduction of the first personal computers, due in large part to the progress made in improving the speed of the computer's central processing unit (CPU). Data is transported to the CPU over electrical wires, processed in the CPU using electrical gates, and moved between the computer's various components over electrical wires or other forms of electrical cabling.

For many of the same reasons that fiber optics has replaced coaxial cable in the long-haul telecommunications market, it is now replacing coaxial cable in shorter distance data transport applications. Computer-to-compute, server-to-server, storage area networking device-to-router, and many other computer box-to-peripheral connections will soon be interconnected mostly via fiber optics. The high data rates at which these networked computer devices will communicate makes fiber optics the most economical and "future-proof" choice.

The use of photonics also leads to a reduction in overall computer size because photonic-based interconnects can be placed more closely together than electrically based wires. The reason for this is that electrical wires tend to radiate like antennas and, if placed too closely together, data on one wire can be received and transmitted by an unintended wire.

In this picture are two high-speed connectors that can handle approximately equal volumes of traffic. However, the optical connector on the left is far smaller than the electrical connector because optical fibers can be placed much closer together than wires in an electrical connector. More advances in computer architecture will become available as photonic means of data transfer begin to appear inside the computer box.

Just as copper-based electrical interconnects proved too power hungry and slow for long-distance data transport so, too, will electrically based data interconnects inside the computer be replaced by photonic technology.

"Inside-the-box" photonic interconnects will be available in two styles. The first approach will embed waveguides or optical fibers in the computer's backplane, much as wires and metallic traces are used today. The second approach will use free space optics, where data is transmitted between nearest neighbor computer boards directly and bypassing the backplane of the computer entirely.

Embedded optical waveguides can be used for piping data across a computer board. These waveguides can send data in straight lines or around bends and include the splitter/combiner shown in the upper right.

An important feature of optical waveguides is their ability to use manufacturing methods already found in the computer industry. Many such processes are currently in development.

In the free space optics approach, a lenselet array would serve to focus light that is emitted from one board onto the detectors that are on the other board. An array of vertical cavity surface emitting lasers (VCSELs) is used to send the data board-to-board. VCSELs are important because they allow data to be easily projected from one board to another and because many of them can be packed into a very small space.

The use of VCSEL and detector arrays means that several emitters can send data across the open space simultaneously. This parallel data transport technique enables establishment of very high-speed data transport channels within the computer.

Farther out in the future, chips will be so large that it will take several steps (or clock cycles) for information to get from one side of the chip to the other. This means that one part of the chip will have to wait a period for data to arrive before it can proceed with a task. This problem will get worse as computer processor chips get larger and transistors get smaller.

If we view the billion-plus computer chip of the future as divided into regions, it resembles a very dense checkerboard arrangement. The different regions of the chip could be grouped by function or capability. Regions might be constructed to contain devices that provide memory, computation, analog-to-digital conversion, specialized processing, or input/output functions. These different regions could communicate via a special network on the chip, much as workstations, computers, and servers are connected by a local area network.

One approach to providing an on-chip, free-space optical interconnect could have the bottom of the interconnect structure consist of VCSEL and detector arrays mounted on top of selected chip regions. The top part of the interconnect structure is an array of focusing mirrors, each element of which can send a data stream to a particular detector array. These mirrors serve to relay information from one chip region to another. Such an arrangement would make for a compact package that is compatible with personal computer design.

One of the most commercially and scientifically successful applications of photonics is imaging. Throughout much of the history of the development of imaging, there has been a strong desire to achieve an accurate reproduction of scenes in accordance with the sensitivity biases of the human eye. However, those parts of the electromagnetic spectrum that fall outside the visible region can be very valuable. For example, infrared cameras can be used to detect heat leaking from buildings. Sampling several regions of the spectrum simultaneously is called “multispectral imaging.” This technique can be quite useful in detecting the presence of some object not normally visible to the unaided human eye.

Multispectral cameras that can simultaneously look in several parts of the spectrum are used in detecting diseased or weather-damaged plants, pollution, and camouflaged objects. Sophisticated software is quite often required to fully interpret the data gathered by these types of imaging systems.

One particularly active area of research involves night vision, infrared imaging systems. These detectors use as the infrared sensitive element a structure called a bolometer, which converts the heat energy given off by an object into an electrical current that can be recorded by the imaging apparatus. A serious problem facing some important types of night vision infrared detectors is the requirement for external cooling.

One novel approach that will yield good sensitivity with no external cooling has thin arms supporting a large-area detector to provide the means by which thermal isolation is achieved. This structure is used to keep the heat energy that falls on one detector element from contaminating nearby elements.

Another important feature of this arrangement is the placement of the readout electronics. Placing this circuitry in close proximity to the bolometer eliminates any need for long, bulky wires to be attached, which, in turn, helps eliminate the need for external cooling. Placing these elements in large arrays forms the basis for the final detector structure. Detectors such as these combine elements of electronics, photonics, and MEMS and use standard, microelectronic, batch-fabrication techniques.

Fiber optic-based communication has had a tremendously successful impact on city-to-city, state-to-state, and country-to-country voice and data communications. This success is due in large part to fiber's more economical ability to carry a higher volume of traffic than coaxial cable. However, the high cost of installing fiber makes it uneconomical for areas where the volume of data traffic might not be very high. In fact, it has been estimated that only about 5 percent of the buildings in North America are within easy reach of optical fiber, and this number is even lower for most countries outside North America.

Alternatives to deploying optical fiber, such as cellular, microwave, and satellite-based approaches, do not have optical fiber's right-of-way problem. However, these other methods can use very expensive equipment (especially satellite) and require special licensing for access to specific parts of the radio spectrum (which is not always available).

One advantage to radio-based technology, though, is its support of mobile connectivity. Increasingly, there is a very strong demand for the deployment of mobile wireless, high-speed services. An approach that offers the opportunity to achieve both the high-speed throughput of fiber optic links and the mobility of radio wireless will be available in the future. This new method is mobile optical wireless.

In its present commercial configuration, free-space laser transmitters and receivers are attached directly to buildings, enabling establishment of high-speed, point-to-point links. While this approach is extremely useful in bringing broadband services to locations that otherwise would not be served, it lacks the mobility of radio wireless solutions.

An additional major complication is the state of development of conventional methods of steering laser beams, which have relied upon large, mechanical, gimbal-type apparatus. While capable of achieving very high levels of pointing accuracy and high-speed communication over great distance, the conventional approach has yielded steering units that are mostly hand-machined and assembled, expensive, and heavy. The key to achieving mobility in optical wireless lies in the development of small, low-power, low-cost, laser beam steering units.

Recent advances in MEMS, liquid crystals, and microdiffractive optic arrays may provide a path for development of mobile optical wireless devices. MEMS devices, which are on the order of hundreds of microns in size, will provide an ultra compact means of steering laser beams.

Another novel approach to development of beam steering devices is the use of liquid crystals. The liquid crystal beam steering device has electrical wires and transparent electrodes on either side, forming a sandwich structure. By applying a voltage to certain parts of the liquid crystal, the index of refraction can be made to change. In this manner, an electrically addressable hologram can be formed. A laser beam striking the liquid crystal from behind could then be split into multiple beams. The liquid crystal approach will someday have the ability to steer multiple beams independently. This will be extremely useful in future applications of mobile optical wireless because it will allow a single user to be simultaneously tied into several network nodes.

The final challenge for photonics lies in the area of service-on-demand networks. The ability to deliver high-quality, high-capacity data networks is a key element of our critical national and defense infrastructure. Unfortunately, our current worldwide network deployment has its roots in the more than 100-year-old voice traffic network. The result is that the data-driven networks of the future will not be able to make efficient use of voice-based systems and deliver the types of services the U.S. will need in times of national emergency or military operations. The reason for this is network congestion caused by optical-to-electrical-to-optical conversions.

An example of this type of impediment is data format and type translation. Data that is generated by one user or network segment often is incompatible with other users or network segments. It's as if different parts of the network speak different languages and, for all practical purposes, this is exactly the case. Some network developers would like to see all networks speak the same language and, thus, end the translation bottlenecks. Unfortunately, this is very unlikely to happen due to the widespread deployment of so many end-user systems that speak only a particular language.

Photonics research in the area of all-optical networking offers an elegant, high-speed, and very robust solution to this problem. All optical networking allows end-to-end transport of all data types without the need for translation at any intervening nodes. Advanced techniques such as ultradense wavelength division multiplexing, direct wavelength conversion, all-optical signal regeneration, optical clock recovery, and all-optical switching might someday make this lofty goal a reality.

In conclusion, photonics has had a very successful impact on U.S. battlefield operations through development of such novel technologies as night vision equipment, laser target designation, laser ring gyros, laser radar, and a variety of imaging systems. Proven in some of the most demanding operational and tactical environments, photonics promises to deliver new capabilities that will enable the United States to dominate all aspects of future warfare.